consistent with the observed distribution of dislocations in crystals. The dislocations nucleation mechanisms in GaAs and in other materials like InP or Si require an understanding of the CRSS at high temperature which is assumed to vary with (i) the native defects concentration and their mobility and (ii) their interaction with dopant or background impurities.

[1]J. B. Mullin, B. W. Straughan, and W. S. Briekell, J. Phys. Chem. Solids **26**, 782 (1965).
[2]R. Zucca, B. M. Welch, P. M. Asbeck, R. C. Edenand, and S. I. Long, *Semi-insulating III-V Materials*, edited by G. J. Rees (Nottingham, 1980), p. 335.
[3]A. S. Jordan, J. Appl. Phys. **51**, 2218 (1980).
[4]A. S. Jordan, J. Crystal Growth **49**, 631 (1980).
[5]A. S. Jordan, R. Caruso, and A. R. von Neida, Bell Sys. Tech. J. **49**, 593 (1980).
[6]A. S. Jordan, R. Caruso, A. R. von Neida, and J. W. Nielsen, J. Appl. Phys. **52**, 3331 (1980).
[7]N. A. Avdonin, S. S. Vakchramiev, M. G. Mil'vidskii, V. B. Osvenskii, B. A. Sakharov, V. A. Smirnov, and Yu. F. Shchelkin, Soviet Phys. **16**, 772 (1972).
[8]M. G. Mil'vidskii, V. B. Osvenskii, and S. S. Shifrin, J. Crystal Growth **52**, 396 (1981).
[9]M. G. Mil'vidskii and E. P. Bochkarev, J. Crystal Growth **44**, 61 (1978).
[10]M. G. Mil'vidskii, V. B. Osvenskii, B. A. Sakharov, and S. S. Shifrin, Sov. Phys. **17**, 1129 (1973).
[11]M. Duseaux (unpublished).
[12]J. P. Farges (private communication).
[13]J. Roksnoer (private communication).
[14]Y. Seki, H. Watanabe, and J. Matsui, J. Appl. Phys. **49**, 822 (1978).
[15]G. Jacob, J. P. Farges, C. Schémali, M. Duseaux, J. Hallais, W. Bartels, and J. Roksnoer J. Crystal Growth **57** (1982).
[16]G. Jacob (unpublished).
[17]J. K. Mackenzie, Thesis, Bristol, 1949.
[18]C. Kittel, *Introduction to Solid State Physics*, 2nd ed. (Wiley, New York, 1957), pp. 536–540.
[19]J. Friedel, *Dislocations* (Pergamon, New York, 1964), pp. 216–219.
[20]K. Kamada and B. K. Tanner, Philos. Mag. **29**, 309 (1974).
[21]S. S. Brenner, J. Appl. Phys. **28**, 1023 (1957).

Mode selection and intensity enhancement of x rays in crystals

Shih-Lin Chang[a)]
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 7000 Stuttgart 80, Federal Republic of Germany

(Received 11 January 1982; accepted for publication 17 February 1982)

Previously unreported intensity enhancement of x rays obtained by two-mode excitation is observed on the direct incident beam of synchrotron radiation. The excitation utilizes the coherent interaction of a six-beam Borrmann diffraction in a perfect silicon single crystal. The experiment provides a means of obtaining nearly divergenceless, monochromatic, spatially coherent, and intense x-ray sources for x-ray diffraction and imaging studies. Single-mode excitation can be achieved by using a thick crystal.

PACS numbers: 61.10.Dp, 61.10.Fr

Anomalously high transmission of x rays through a perfect crystal is usually observed in multiple Borrmann diffraction.[1–6] In a common n-beam ($n > 2$) diffraction experiment, the dynamical interaction among the n diffracted beams generates wavefields propagating in $2n$ different ways inside the crystal, the so-called modes of wave propagation.[7] The factor of 2 is due to the two polarizations: σ polarization is perpendicular and π polarization is parallel to the plane of incidence. The fraction of the incident energy associated with a given mode is defined as the excitation of mode. Those modes with wavefield node coincident with the atom sites have extremely low absorption. Those modes are responsible for the anomalous transmission of x rays through the crystal.

There is a special six-beam case, (000) ($0\bar{4}4$) ($2\bar{2}0$) ($\bar{2}02$) ($2\bar{4}2$) ($\bar{2}2\bar{4}$), in which six reciprocal lattice points form a regular hexagon, shown in Fig. 1. Two of the resulting twelve modes have linear absorption coefficients μ, almost equal to 0, i.e. [Eq. (4.15) of Ref. 2],

$$\mu = \kappa(\Phi''_{000} - \Phi''_{\bar{2}02} - \Phi''_{2\bar{2}4} + \Phi''_{0\bar{4}4}) \approx 0, \tag{1}$$

at the exact six-beam diffraction point. The term Φ'' is the

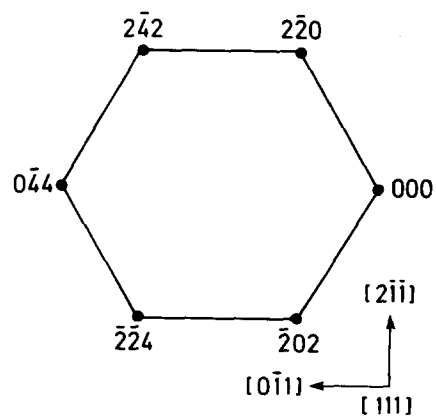

FIG. 1. Representation of the six-beam case in reciprocal space.

[a)]One leave from Instituto de Física, Universidade Estadual de Campinas, Campinas, S. P. 13100, Brazil.

0003-6951/82/090793-03$01.00

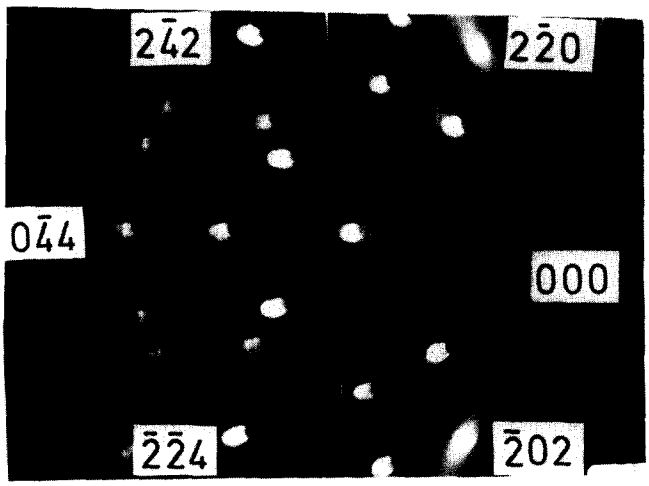

FIG. 2. Laue transmission photograph for the six-beam case at $\lambda = 1.0$ Å. The distortion of the diffraction image is due to the fact that the camera was not set exactly parallel to the crystal surface, i.e., (111) planes. The six diffracted spots form a regular hexagon.

imaginary part of the electric susceptibility of the reflection involved. κ is a proportionality constant. By using a rather thick perfect crystal, only the two modes can be effectively excited and the rest of the modes are suppressed by the crystal absorption. These two residual modes should, in principle, provide an intense, monochromatic, and extremely parallel transmitted beam. The search for observing this effect has long been carried out.[2,8–10] However, no success in experiments has been reported so far.

In this letter I report, for the first time, the observation of this unusual anomalous transmission of x rays through a perfect silicon single crystal on the direct incident beam of synchrotron radiation. The DORIS storage ring of DESY in Hamburg, Germany, is used.

The experiment is performed by aligning a [111] cut platelike perfect silicon crystal for (0$\bar{4}$4) reflection at the wavelength $\lambda = 1.0$ Å. The crystal thickness is 3 mm. The angular divergence of the incident beam is about 20″. The Laue transmission photograph, Fig. 2, shows this six-beam diffraction for $\lambda = 1.0$ Å. The direct incident beam is attenuated by a beamstop, which consists of a 1-mm-thick lead and a 3-mm-thick aluminium plate. The camera is also shielded by aluminium and lead foils to suppress the high background from the white radiation. The enhanced transmitted intensity on the direct beam, (000) (inside the shadow of the beamstop on the right side of Fig. 2), is readily observable. When the crystal is set at the Bragg angle of (0$\bar{4}$4) reflection for $\lambda = 1.54$ Å, the intensity enhancement of the direct transmitted beam at the six-beam point is reinforced. This is shown in Fig. 3. The enhanced spot has an angular divergence of about 2″. The shape of the direct beam is due to the geometry of a collimator at the exit of the synchrotron beam line.

A computer program, based on Ref. 6, for n-beam dynamical calculation is employed to account for the experimental results. The calculated transmitted intensity of the (000) reflection is shown in Fig. 4. Diffracted intensities less than 10^{-2} are too weak to be observed in Fig. 3. The agreement between the experiment and the calculation is seen.

FIG. 3. Image of the direct (000) beam at the exact six-beam diffraction position for $\lambda = 1.54$ Å.

Since the synchrotron radiation is linearly polarized in the π direction, there are three modes which are not excited due to this polarization effect. The two most strongly excited and lowly absorbed modes, denoted as modes 1 and 2, have the absorption coefficients equal to 0.19 and 0.87 cm^{-1}, respectively. The corresponding excitations of the modes are 10.1 and 16.7%. The rest of the modes having absorptions ranging from 13.17 to 543.48 cm^{-1} are suppressed by the crystal. Only modes 1 and 2 thus contribute to the diffracted intensity. Mode 1 has minimum intensities at the atom sites, while mode 2 has maximum intensities near (but not at) the atom sites.[10] The difference in wave vector between the two modes is only 24.55 cm^{-1} in the [111] direction. The intensity distribution for these two modes projected on the (111) plane at the exact six-beam point is similar to Figs. 4(c) and 4(d) of Ref. 9, except that the intensity maxima are squeezed along the [0$\bar{1}$1] direction. For the crystal settings slightly off, for example by 1″, the six-beam position, the absorption of these two modes increases by a factor of 30. Thus, a sharp intensity enhancement within a 2″ angular range is expected and observed experimentally (Fig. 3). This intense beam is nearly nondivergent, monochromatic, and spatially coherent.[9,10]

If a 5-cm-thick perfect silicon crystal is used, mode 2 can be almost completely suppressed by the crystal absorption. The intensity ratio between modes 2 and 1 is estimated about less than 5%. Single-mode excitation can therefore be achieved.

In conlcusion, the use of this six-beam diffraction and a linearly polarized source, like synchrotron radiation, permits the selection, for example, of reduction of excited modes of x rays in crystals. The anomalously transmitted

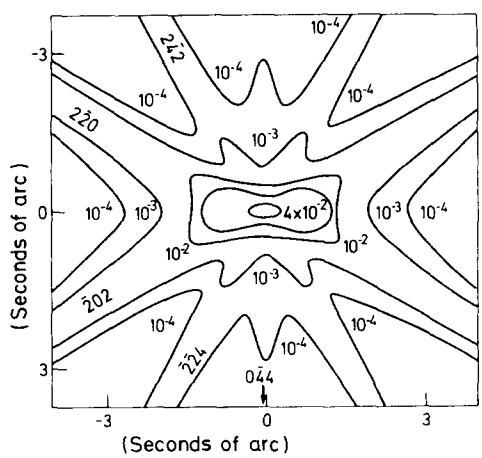

FIG. 4. Calculated intensity distribution of the direct (000) beam at the exact six-beam point for $\lambda = 1.54$ Å. The axes represent the vertical and horizontal beam divergence.

intensity at the exact six-beam diffraction point provides a new source, with monochromaticity, exceedingly low divergence, and single-mode excitation, for x-ray diffraction and imaging studies.

In addition, for the efforts towards realizing gamma-ray lasers,[11] this low photoelectric absorption in the six-beam Borrmann effect and the reduced number of modes excitation give a possible condition to lower the critical inversion density needed for net gain by stimulated emission.[12]

The author is indebted to Professor C. Kunz and Dr. E. Koch and Dr. W. Graeff for arranging the beam time at the HASYLAB of DESY. The help of providing instruments and technical assistances from Professor G. Hildebrandt, Dr. J. D. Stephenson, Dr. M. Umeno, and Dr. W. Graeff, and the critical reading and helpful discussion from Professor H. -J. Queisser are also gratefully acknowledged.

[1]G. Borrmann and W. Hartwig, Z. Kristallogr. **121**, 401 (1965).
[2]T. Joko and J. Fukuhara, J. Phys. Soc. Jpn. **22**, 597 (1967).
[3]G. Hildebrandt, Phys. Status Solidi **15**, K131 (1966).
[4]P. P. Ewald and Y. Heno, Acta Crystallogr. Sect. A **24**, 5 (1968).
[5]S. Balter, R. Feldman, and B. Post, Phys. Rev. Lett. **27**, 307 (1971).
[6]B. Post, S. L. Chang, and T. C. Huang, Acta Crystallogr. Sect. A **33**, 90 (1977).
[7]E. J. Saccocio and A. Zajac, Acta Crystallogr. **18**, 478 (1965).
[8]T. C. Huang, M. H. Tillinger, and B. Post, Z. Naturforschteil A **28**, 600 (1973).
[9]M. Umeno, Phys. Status Solidi A **37**, 561 (1976).
[10]M. Umeno, Phys. Status Solidi A **38**, 701 (1976).
[11]G. C. Baldwin, J. C. Solem, and V. I. Gol'danskii, Rev. Mod. Phys. **53**, 687 (1981).
[12]G. C. Baldwin, J. P. Neissel, J. H. Terhune, and L. Tonks, Trans. Am. Nucl. Soc. **6**, 178 (1963).

Diffusion of arsenic in polycrystalline silicon

B. Swaminathan, K. C. Saraswat, and R. W. Dutton
Integrated Circuits Laboratory, Stanford University, Stanford, California 94305

T. I. Kamins
Hewlett Packard Laboratories, Palo Alto, California 94304

(Received 30 November 1981; accepted for publication 21 February 1982)

The diffusion of arsenic in polycrystalline silicon films has been studied over the temperature range 750–950 °C and for grain sizes 210–510 nm. Rutherford backscattering spectrometry was used to measure the concentration profiles of arsenic, initially introduced into the polysilicon by ion implantation, after various annealing steps. The concentration profiles were found to be determined by a combination of two factors—the low diffusivity in the bulk of the grains and the much higher diffusivity in the grain boundaries. The diffusivity of arsenic in the grain boundaries was independent of concentration, with an activation energy of 3.9 eV, very close to that of the low-concentration arsenic diffusivity in single-crystal silicon. However, the value of the diffusivity was $8.6\times 10^4 \exp(-3.9/kT)\text{cm}^2/\text{s}$, four orders of magnitude higher than the single-crystal value. The diffusivity in the interior of the grains was the same as that in single-crystal silicon.

PACS numbers: 66.30.Jt

The characterization of the diffusion of dopants in polycrystalline silicon is important for several device applications. In silicon metal-oxide-semiconductor field-effect transistors, the polysilicon gate should be diffused with a uniform heavy concentration of dopant without penetration of the dopant to the channel region through the thin gate oxide. In buried contacts where the substrate is doped by diffusion of dopant from a polysilicon layer, the impurity profile in the substrate is influenced by the diffusivity in the polysilicon. The performance of high value polysilicon resistors, used in static memory, is limited by the diffusion of dopant primarily along grain boundaries, from the highly doped contact area to the lightly doped resistor area. Diffusion along the grain boundaries will also limit the performance of devices fabricated on large-grained polysilicon thin films obtained by laser recrystalization.

Not much work has been reported on the diffusion of dopants in polysilicon. Kamins *et al.*[1] measured the diffusivity of phosphorus and boron in thick films of polysilicon, using staining to reveal the junctions. Tsukamoto *et al.*[2] and Ryssel *et al.*[3] used Rutherford backscattering spectrometry to measure the diffusivity of arsenic in thin films of polysilicon. In this work, we have also used Rutherford backscattering spectrometry for similar measurements. Our results are however quite different from those of Refs. 2 and 3.

⟨100⟩ oriented silicon wafers with 100 nm of thermally grown silicon dioxide were used as substrates for the deposition of 1000-nm-thick layers of polysilicon in a low-pressure chemical vapor deposition reactor at a pressure of 0.2 Torr and a temperature of 625 °C. To study the effect of changing grain size and structure on the diffusivity of arsenic, some of the polysilicon films were annealed in a dry-nitrogen am-

 0003-6951/82/090795–04$01.00